# ICESat over Arctic sea ice: Interpretation of altimetric and reflectivity profiles

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[1] We provide an assessment of the ICESat altimeter for studying the Arctic Ocean and examine the magnitude of the large- and small-scale expressions of geophysical processes embedded in the elevation profiles. This analysis includes data from six surveys. At the large scale the response of the ice-covered ocean to atmospheric loading is near ideal (i.e., approximately $-1$ cm/hPa). After removal of the inverted barometer effects and best available geoid the elevation signal is still dominated by unresolved geoid residuals ($\sim$0.4 m) that can be seen in the similarity of the remaining spatial patterns. Seasonal differences in elevations over multiyear ice are consistent with snow depth climatology; the broad differential spatial patterns are indicative of interannual differences in multiyear ice coverage associated with advection. Patterns in the derived surface roughness fields correspond to the seasonal and perennial ice zones seen in QuikSCAT data. At the small scale, near-coincident RADARSAT imagery provides a spatial context for understanding the signature of the observed elevations, waveforms, and reflectivity, in particular, those associated with thin ice, open water, multiyear ice, and ridges. The precision of the elevation estimates measured over relatively flat sea ice, identified in synthetic aperture radar (SAR) imagery, is $\sim$2 cm. The unambiguous identification of ridged areas in coupled ICESat/RADARSAT analysis could be used to enhance the utility of SAR imagery for examining ridge distributions. Over a 20 day period we monitored the evolution of the reflectivity of a newly opened lead. The steep increase in reflectivity due to snow coverage suggests that dips in ICESat reflectivity are likely areas of thin ice and could serve as a basis for selection of tie points for use as sea level reference. Identification of these tie points is crucial for accurate estimation of sea ice freeboard.

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## 1. Introduction

[2] ICESat was launched in January 2003. This is the first laser altimetry mission to provide large-scale mapping of the Arctic Ocean. The primary objective of the ICESat mission is to measure changes in the elevation of the Greenland and Antarctic ice sheets [*Zwally et al.*, 2002]. One secondary objective is to provide estimates of sea ice thickness, a key parameter of interest to the sea ice and climate communities. As laser altimeter observations of the sea ice cover are relatively new, the geophysical utility and limitations of these sea ice observations remain topics of investigation. A brief examination of the uses of the ICESat data set for sea ice investigations can be found in *Kwok et al.* [2004]. The present note expands on this work and focuses on the amplitude of the large- and small-scale geophysical signal embedded in the altimetric profiles. Even though we do not address directly the topic of sea ice thickness retrieval in this note, the analysis here contributes to an understanding of the natural variability in ICESat elevations and the uncertainties that limit the achievable accuracy in the estimation of sea ice freeboard and thickness.

[3] ICESat carries the Geoscience Laser Altimeter System (GLAS). This instrument consists of two channels, at 1064 nm and 532 nm, the longer wavelength of which is used for surface altimetry. With a beam width of $\sim$110 μrad and a pulse rate of 40/s, it samples the Earth's surface from an orbit with inclination of 94° with footprints of $\sim$70 m in diameter spaced at $\sim$170 m intervals. The Arctic Ocean is covered to 86°N. Expected accuracy in elevation determination over relatively low-slope surfaces (e.g., ice sheet) is $\sim$14 cm. ICESat data products provide the surface elevation, relative to an ellipsoid, derived from the altimetric waveforms. On a broad scale, the highly reflective air/snow interface dominates the echo energy from the sea ice cover. However, at a spot size of 70 m, smaller-scale features also modulate the amplitude and character of the waveforms. Ice thickness, snow depth and surface height distributions due to ridges, hummocks, and ice rafts all contribute to the variability of the reflected energy and the broadening of the echo waveforms. Detailed surface information is contained in the data although the interpretation requires supporting observations at close to the same spatial resolution. Near coincident synthetic aperture radar (SAR) imagery, with comparable resolution, provides a spatial context for examining these signatures and their use. With RADARSAT observations, *Kwok et al.* [2004] demonstrated an approach for unambiguous identification of thin ice and open water segments in ICESat elevation profiles. These segments of open water or thin ice (less than several centimeters thick) are crucial for locating the sea surface; a prerequisite for estimating the local sea ice freeboard in ICESat elevation as current knowledge of the time-varying sea surface height is far from adequate for direct freeboard

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retrieval without the introduction of tie points. Supporting high-resolution imagery is critical for interpreting small-scale variability in the elevation profiles. In this paper, we use coincident SAR data to study the elevation and reflectivity signatures of thin ice and open water in new openings, ridges, and undeformed ice. The steep increase in reflectivity of lead ice, due to rapid snow coverage in its natural environment, suggests an algorithmic basis for identification of such segments in ICESat elevation without the use of SAR imagery.

[4] Other contributions to elevation variability observed by ICESat include geoid undulations, sea surface response to atmospheric pressure loading, tides, and dynamic topography of the ocean. ICESat data products provide estimates of geoid and modeled tide elevations. Residuals after the removal of these terms are large, especially at the length scale of the ICESat footprint. The magnitude of these residuals are examined; if separable from each other they can be used to improve models of tides, geoid, dynamic topography, and the response of the Arctic Ocean to atmospheric forcing. Our current knowledge of these terms and their expected variability are discussed.

[5] This work represents a first-order assessment of the characteristics and utility of ICESat data for studying the Arctic Ocean. It examines the magnitude of the large- and small-scale expressions of geophysical processes embedded in the ICESat data. The retrieval of freeboard and thickness estimation is not within the scope of this paper. The paper is organized as follows. Section 2 describes the data sets used in this paper. Specific ICESat parameters used in our analyses and relevant ICESat instrument and data characteristics are described in section 3. The component terms that contribute to the variability in ICESat elevations are discussed in section 4. Section 5 discusses the large-scale patterns in seasonal and interannual differences in ICESat elevations. Small-scale features that are observed using near coincident ICESat/RADARSAT are examined in section 6. The last section summarizes the paper.

## 7. Conclusions

[39] The present examination of the utility of ICESat data for studies of the Arctic Ocean is by no means exhaustive. It represents a more detailed assessment, compared to the first look offered by *Kwok et al.* [2004] of the quality and the potential of the data set; these first steps are important for understanding the capabilities and limitations of the instrument for making observations of the sea ice cover and the polar oceans. In this section, we summarize the salient points.

[40] An issue that affects the ICESat elevations is the saturation of the GLAS instrument. The distortion of the waveform depends on echo energy; all returns with energy >9 fJ are affected by some level of saturation. On the basis of ground testing, moderate levels of saturation and their effects on elevation retrieval are predictable and can be corrected. Examples here show that these corrections seem effective. However, the level of saturation of waveforms from high reflectivity and near-specular returns are beyond the range of valid adjustments. In these cases, caution should be exercised in using these elevation samples.

[41] On a broad scale, residual signals of the geoid, the atmosphere, tides, and dynamic topography in the ICESat profiles are discussed. Response of the sea ice cover to the inverted barometer effect is near ideal. It is evident that the IB correction significantly decreases the variance of the ICESat fields and is an important step in using the data. By far, the residuals are dominated by geoidal height. This can be seen in the consistency of the spatial patterns of the residual fields (Figure 5) from all six surveys. Features in the residual fields correspond to bathymetric relief with high surface slopes. This suggests that these residuals could be, in turn, used to improve the representation of smaller-scale features in the Arctic geoid. A number of investigators are moving in this direction. The variability of the observed elevation due to dynamic topography remains a question. On the basis of the magnitude of these residuals, it is clear that frequent sea level references are required for accurate determination of freeboard.

[42] Seasonal and interannual differences in ICESat elevations are consistent with expectations, i.e., winter−fall > 0. Since basal ice growth is slower over thick multiyear ice, the larger contribution of snow depth to sea ice freeboard suggests that it may be possible to obtain some level of estimate of the snow depth over MY ice because ice growth over MY ice can be roughly modeled. A denser temporal sampling of the ice cover would provide a more usable trend in freeboard for surface heat balance calculations and the development of a better snow climatology.

[43] At the small scale, RADARSAT imagery provides a spatial context, along with the vertical dimension of the altimeter profiles, for better interpretation of the small-scale characteristics of the ICESat elevations. In one examination, the steep increase in reflectivity in a new opening is consistent with the prompt coverage by a snow layer. In situ observations support that only 1–2 cm of snow cover is required to nearly mask the reflectivity of the underlying ice; this snow-covered thin ice is indistinguishable from the adjacent snow cover. Thin ice is thus likely when coincident dips in reflectivity and elevations are encountered in ICESat samples. This suggests an algorithmic basis for identifying samples of thin ice and open water in ICESat data, i.e., low-reflectivity samples are associated with samples of thin ice. Even though *Kwok et al.* [2004] demonstrated the use of sequential RADARSAT imagery to locate new openings in the ice cover, this exclusive use of ICESat data would allow for a simpler procedure for identifying thin ice areas and less dependence on the time-consuming process of locating openings in sequential SAR imagery.

[44] In the past it has always been thought that high backscatter linear features were associated with ridges, but we believe that this is the first observed correlation between spikes in surface elevation in ICESat profiles and SAR backscatter. This is complementary to the linear relation between the draft of ridges and radar backscatter observed by *Melling* [1998]. Ridge zones (or keels) modify the air/water stress components in the momentum balance and create gradients in small-scale ice motion and stress distributions within the ice cover. Although outside the scope of the present analysis, the use of these coincident data sets to improve the understanding the variability of surface drag is worthy of closer examination.

[45] ICESat observations over the Arctic Ocean show promise in providing a variety of geophysically useful sea ice observations. It is unfortunate that the limitations of the laser lifetime have not permitted the originally intended continuous operation, but the revised measurement strategy is providing multiyear observations with surveys of 33 days each during winter, spring, and fall. Of immediate geophysical interest is the development of a robust procedure, with quantifiable uncertainties, for location of the sea surface that allows for better separation of the processes embedded in the retrieved elevation and the estimation of sea ice freeboard.